Remote Sensing of Environment 112 (2008) 3604–3617

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Water level fluctuations derived from ENVISAT Radar Altimeter (RA-2) and *in-situ* measurements in a subtropical waterbody: Lake Izabal (Guatemala)

Camilo Ernesto Medina *, Jesus Gomez-Enri, Jose J. Alonso, Pilar Villares

Applied Physics Department, CASEM (University of Cadiz), Spain

ARTICLE INFO

Article history:
Received 28 November 2007
Received in revised form 30 April 2008
Accepted 3 May 2008

Keywords:
Altimetry
Lake levels
Hydrology
Lake Izabal

ABSTRACT

The use of remote sensing techniques in monitoring inland waters has become a powerful tool, considering the amount of ungauged waterbodies all over the world. The water mass balance is an essential subject to take into account in water management activities. The level changes of a lake surface are an indicator of the water mass balance of a basin since they reflect the water storage variations. Space borne altimeters have been successfully used in the last decade to measure lakes, rivers and wetland stages. This study presents the first analysis of Lake Izabal — the biggest lake of Guatemala (Central America) — water level fluctuations using altimetry data and *in-situ* measurements. Water level variations were obtained from Envisat Radar Altimeter (RA-2) Geophysical Data Records coupled with *in-situ* measurements. The analysis period included three complete years (2004 to 2006). The rainfall and temperature records over the catchment were analyzed considering that the amount of water feeding the lake, either by the tributaries and/or the groundwater, is driven by the climatic conditions over the lake's catchment. The results obtained show a good agreement between both, altimeter and *in-situ* datasets (correlation coefficient: 0.83 and rms error: 0.09 m). Lake Izabal water level fluctuations have a seasonal signal forced by the rainy and dry climate seasons in the region. An abrupt lake level rise was found in July 2006 which is correlated to abnormal precipitations in June. We found a connection between the higher/lower extreme values in the lake level variations with rainfall anomalies produced by regional climate changes forced by El Niño Southern Oscillation and the Tropical North Atlantic anomaly.

1. Introduction

Lakes water levels have a dynamic behaviour and its variations are an essential subject for water resources research and management. These variations have a wide range of time scales from short-term (daily) to long-term (yearly) scales. Most of the physical and ecological processes in a lake are directly related with its water level fluctuations. Among others, the lake level variations might affect the residence time of the water, nutrients concentration, heat content, circulation patterns, wind-driven resuspension, biologic activities and changes in the trophic chain. In addition, the water mass balance of the lake watershed depends on level fluctuations also, since they reflect volume variations of the storage water.

The ecosystem on a lake shows a complex interaction between weather conditions, surface and underground waters. Lakes water level variations are generated by: fluctuations of the water volume, pressure changes over the lake surface, circulation processes, wind events and tides. From all of them, the water volume fluctuations are the main responsible of the water level variations (Mercier et al., 2002). Volume changes in the water are driven by precipitation and evaporation over the lakes surface, rivers inflow and outflow, and underground inflow and ground seepage. The amount of water that fed the lake depends on climatic conditions over the hydrologic basin, its geomorphology and level of human activities, such as irrigation and drainage systems (Birkett, 1995; Birkett, 2000; Crétaux et al., 2005; Mercier et al., 2002). The latter found that the time difference between the strongest rainfall over 12 African basins and their corresponding lake level variations was about 1–3 months. Part of this delay corresponds to the time necessary for water to saturate the soils and to reach the lakes. In addition, lakes are known to be sensitive to local and regional climate changes since these changes affects the amount of precipitation, temperature, winds, humidity and evaporation (Crétaux & Birkett, 2006; Mercier et al., 2002).

Water stages of lakes have been traditionally gauged *in-situ*. Nevertheless, field measurements need human and economic resources. Considering that most of the lakes around the world are remotely located, a broad number of them are not being routinely gauged especially in developing countries. Although, radar altimetry technique was developed to measure over ocean surfaces, it has recently provided new means for monitoring inland water stages (Birkett, 1995). Radar altimetry has been, successfully, used in deriving the water level of ungauged inland waterbodies such as rivers, lakes and wetlands. Previous studies have combined *in-situ* measurements

* Corresponding author.
E-mail address: camilomedi@gmail.com (C.E. Medina).

0034-4257/$ – see front matter © 2008 Elsevier Inc. All rights reserved.
doi:10.1016/j.rse.2008.05.001

with altimetry to monitor the water stages of a broad variety of such kind of waterbodies. Birkett (2000) combined lake level variations derived from Topex/Posseidon (T/P) with inundated area variations observed from NOAAs AVHRR satellites to determine water volume variations of Lake Chad. Mercier et al. (2002) used T/P data to evaluate the lake level fluctuations of 12 African lakes, and their relationship with climate changes. More recently, Frappart et al. (2006) evaluated the performance of the ENVISAT (ESA) mission Radar Altimeter (RA-2 henceforth) for continental water height measurements. Crétaux and Birkett (2006), showed in their study the potential of altimetry in this particular matter by reviewing several test case studies on a diverse waterbodies selection.

Lake Izabal (Guatemala) has a great importance to the country, and its physical features are poorly known (URL, 2002). Besides scientific and ecological points of view, the knowledge of its level fluctuations has social effects because the lake resources support the economy of communities settled around the lake. The main objective of this study is to estimate water level fluctuations of Lake Izabal using derived water levels from the Radar Altimeter RA-2 on-board ENVISAT and *in-situ* water level measurements. We will analyze the relationship of these variations with local weather conditions and regional climate changes. Although Lake Izabal is being already monitored by *in-situ* measurements (ground gauge), radar altimetry information is useful to have precise budget errors giving the order of magnitude of confidence for waterbodies with same geomorphologic characteristics in some other remote areas. The paper is organized as follows: Section 2 delineates the Lake Izabal settings. Section 3 describes both datasets and methodology used to estimate the lake level fluctuations. The results obtained, including the seasonal and interannual fluctuations observed are presented in Section 4. The discussion concerning the fluctuations found based on a climatologic–geographic analysis (relationships with the local climate conditions) is in Section 5. We will also discuss the relationship between the fluctuations with regional climate changes produced by El Niño Southern Oscillation (ENSO) and the Tropical North Atlantic anomaly. Finally, the main conclusions are presented in Section 6.

2. Lake Izabal settings

Lake Izabal is the biggest lake in Guatemala (Fig. 1). It is located in the Northwest side of the country, at 15°30′ N and 89°10′ W. It surface extents over 717 km^2, and it is a lowlands water body since its surface height is, approximately, 10 m above the Caribbean Sea mean sea level (Arrivillaga, 2002). Lake Izabal main tributary is the Polochic River, which discharges around 70% of the lakes water input (Basterrechea, 1993). The water outlet is Dulce River, which connects Lake Izabal with the Caribbean Sea through a longitude of 42 km. The lake, its tributaries and outlet, constitute the biggest aquatic ecosystem of Guatemala, named as Lake Izabal–Dulce River System. The ecosystem works as habitat of a broad diversity of wildlife species. The appropriate knowledge of the Lake Izabal water level variations would contribute to improve its management, which is of great importance to the country because of its ecologic and social benefits. The whole system plays a key role in tourism and economic activities, food security, maritime transport and biodiversity conservation.

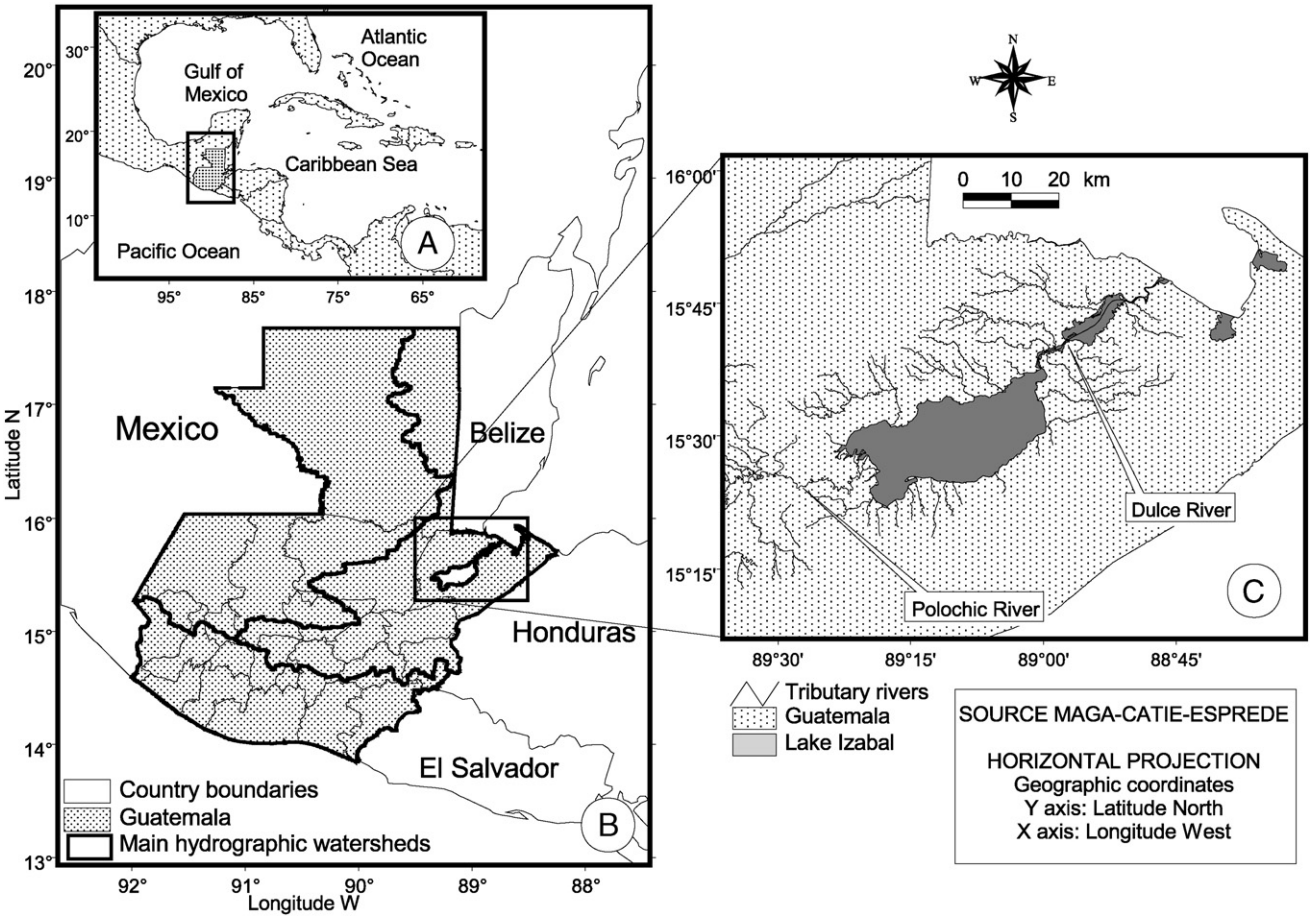

Fig. 1. A) Localization of the Republic of Guatemala in Central America, showing the three main hydrologic watersheds: Gulf of Mexico, Pacific Ocean and Caribbean Sea. B) Geographical situation of Lake Izabal within the country. C) Map of Lake Izabal, its affluent, the Polochic River and outlet (Dulce River).